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C.W. Schmidt and M. Popovic

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

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Duoplasmatron Source Modifications for $^3He^+$ Operation

C. W. Schmidt and M. Popovic
Fermi National Accelerator Laboratory, MS 307, P.O. Box 500, Batavia, IL 60510

A duoplasmatron ion source is used to produce 25 mA of $^3He^+$ with a pulse width of ~80 ms at 360 Hz for acceleration to 10.5 MeV. At this energy, ^3He striking water or carbon targets can produce short lived isotopes of ^{11}C, ^{13}N, ^{15}O and ^{18}F for medical positron emission tomography (PET). A duoplasmatron ion source was chosen originally since it is capable of a sufficient singly-charged helium beam with an acceptable gas consumption. Stable long-term operation of the source required a change in the filament material to molybdenum, and a careful understanding of the oxide filament conditioning, operation and geometry. Other improvements, particularly in the electronics, were helpful to increasing the reliability. The source has operated for many months at ~2.5% duty factor without significant problems and with good stability. We report here the effort that was done to make this source understandable and reliable.

I. INTRODUCTION

An accelerator for producing short-lived positron emitting isotopes of ^{11}C (20 min), ^{13}N (10 min), ^{15}O (122 sec) and ^{18}F (110 min) for medical positron emission tomography (PET)[1] came to Fermilab in 1995. This accelerator was to be upgraded, made operational and used for studies in accelerator, targetry, isotope production and radiochemistry. The basic premise of this project uses ^3He to reduce radiation and shielding as compared to using protons or deuterons. Four RFQs are used for the acceleration to 10.5 MeV. The first RFQ accelerates singly-charged $^3He^+$ to 1 MeV which is then stripped to $^3He^{++}$ to improve the acceleration efficiency in the final three RFQs. The estimated isotope production rate requires an average of 75 particle μA (150 electrical μA) on target. To achieve this the ion source has to provide 25 mA of 80-μs long pulses at 360 Hz (~2.5% duty factor).[2]

II. ION SOURCE

A duoplasmatron ion source was chosen early for this project because it is well understood (at least for protons), has good gas efficiency, high current, low emittance, and is commercially available. A concerned disadvantage was the potentially low filament lifetime due to the high duty factor. The low charge state, $^3He^+$, was also undesirable but sources that might produce $^3He^{++}$ (ECR or volume plasma sources) were highly questionable for this application.[3]

The source presently operates with a plasma (arc) current and voltage of 50-60 A and 120-140 V using a oxide-coated heated filament to provide the plasma electrons. The plasma diffuses through the intermediate electrode and is compressed by the source magnetic field between the intermediate electrode and the anode, Fig. 1. Sufficient plasma passes through the 0.5 mm diameter anode aperture to fill the plasma cup to saturation. The extraction electrode has an electron trap, as shown in Fig. 2. The injected beam energy to the first RFQ is 20 keV so the source and its relevant electronics are at +20 kV. The

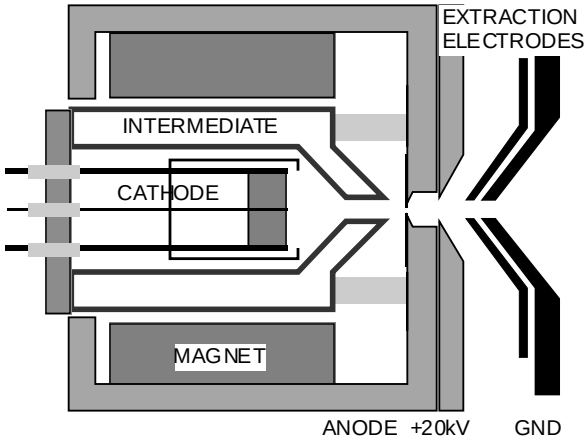

FIG. 1. PET duoplasmatron ion source.

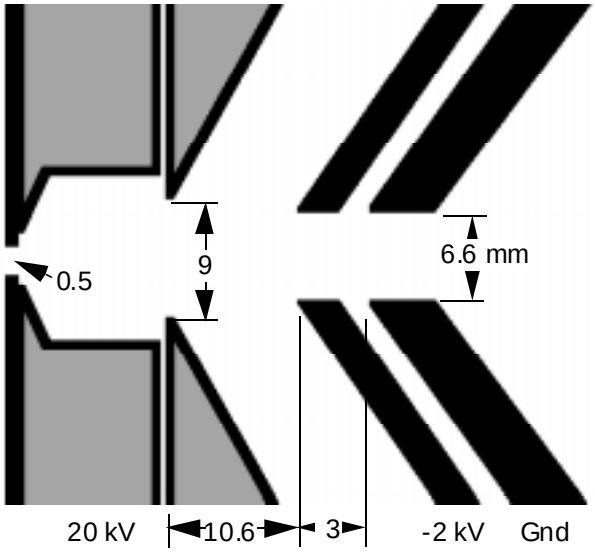

FIG. 2. Extraction geometry.

electron trap operates at ~-2 kV so the extraction field is ~2.0 MV/m. With a Pierce geometry and an extraction aperture of 6.6 mm the Child limit for $^3He^+$ current is ~26 mA. A beam current of 25-26 mA for $^3He^+$ is typical.

The emittance at 20 kV following one solenoid

focusing magnet in the low-energy transport is 24 π cm mr for 90% of the beam.

III. FILAMENTS

To achieve a useful lifetime, a few months, it was necessary to make significant changes to the filament. The original filament, made of nickel wire mesh, would not withstand the heating by the plasma at this duty factor (~2.5%). Heating and helium bombardment would make the nickel brittle so that it cracked, obtained holes and broke within a few days. Changing to a molybdenum wire mesh for the filament has given several months of good operation. With molybdenum there is significantly less damage from helium bombardment so the mesh remains flexible throughout its lifetime. The higher melting point of molybdenum gives more latitude to conditioning and heating the filament.

To use molybdenum a few tricks had to be developed. Spot welding molybdenum is rather difficult; like tungsten, it is hard to make a good bond. However spot welding molybdenum to nickel works well, so the molybdenum mesh was spot welded to nickel rods for current leads and support, FIG. 3. Since the rods are relatively large they do not get hot enough to melt. In places where the molybdenum mesh is folded for additional strength, a thin strip of nickel is placed between the fold to strengthen the weld. This has made working with molybdenum filaments rather simple and easy.

It was also important to understand the mechanism for conditioning the oxide coating on the filament. The coating material begins as a mixture of $BaCO_3$ and $SrCO_3$ - usually called a "radio mixture" in the electrochemical industry. As a powder it is mixed with a liquid hydrocarbon, banana oil or similar solvent, to form a slurry for painting onto the mesh or into which the mesh can be dipped. It is allowed to dry and the painting or dipping repeated until a thick coating is formed. After the filament has fully dried it is heated in air to ~300^{o}C until the smoking has stopped. This burns away the hydrocarbon binder. The final conditioning, to convert the carbonate to an oxide, is done under a good vacuum in a bell jar vacuum system or in the source. $BaCO_3$ decomposes to give off CO_2 at ~950^{o}C with the final conversion to BaO taking place at 1100-1150^{o}C. Thus it is important to reach a high temperature to fully produce the oxide coating.[4,5] During the heating, outgassing may be noticed first at a few hundred degrees from water vapor and hydrocarbons which soon declines. As the temperature is increased to many hundred degrees (800-900^{o}C), large amounts of CO_2 are liberated. The filament temperature should be increased slowly so the pressure does not exceed 0.2 Torr. The filament should be heated until the outgassing ceases. Once the outgassing ends and the vacuum is 10^{-5} Torr or better, activation and testing is done by placing several hundred volts between the filament (negative) and the heat shield or a close metal surface. When fully activated the emission should be several hundred milliamperes at 100 V or less. If conditioned in the source the process is very slow due to the small source aperture unless alternate pumping of the filament chamber is provided. However, once activated the source is ready to operate. If activated in a separate vacuum chamber the filament can be stored until needed. Storage in an inert atmosphere is desirable. If transferred in air from the vacuum system to the storage container or to the source, some of the oxide will convert to a hydroxide ($Ba(OH)_2$). Once placed in the source this filament will need to be conditioned and activated but the outgassing is less and the time is much shorter than for a fresh filament.

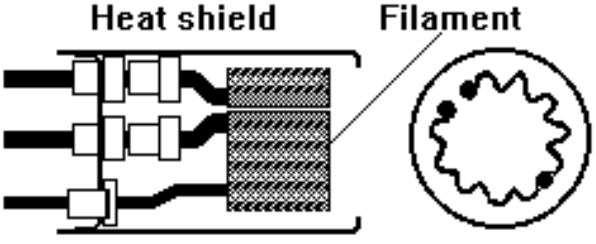

FIG. 3. Source filament.

The source is started on ^{4}He gas with the arc voltage and gas flow set high. For filaments with low emission a small burst of gas may be needed to start the arc. With the source operating at the full duty-factor the filament temperature rises rapidly so the filament current must be lowered. A thermocouple has been placed on the filament to give a relative measure of its temperature. This has been valuable in understanding the filament heating and controlling the temperature. Once the plasma is stable the arc, gas and filament parameters can be adjusted for nominal operation.

IV. GAS OPERATION

Since ^{3}He is relatively expensive, ~$100 per liter, the source is started and operated on ^{4}He whenever beam is not needed. Changing from one gas to another takes only a few minutes. In operation the source requires 2-3 sccm of ^{3}He or ~1 liter per an 8 hr day. No attempt is made to recover the ^{3}He. The gas consumption was reduced by decreasing the source aperture to 0.5 mm (20 mils) which still allows sufficient plasma to fill the plasma cup.

V. ARC POWER SUPPLY

Significant advancement has been made in solid state devices so that SCR type devices which could only switch-on high currents are now able to turn high currents on and off with a small gate pulse. These devices known as IGBTs greatly simplify and improve the efficiency of high current pulsed power supplies such as the arc modulator, see Fig. 4. The arc modulator has thus been reduced to essentially three parts. A capacitor bank or better yet a PFN (pulse forming network) to store and provide energy during the pulse, a charging power supply to re-charge the capacitors between pulses and an IGBT device to switch the pulse on and off. A modulator of this type has been operating for over a year switching 50-100 A,

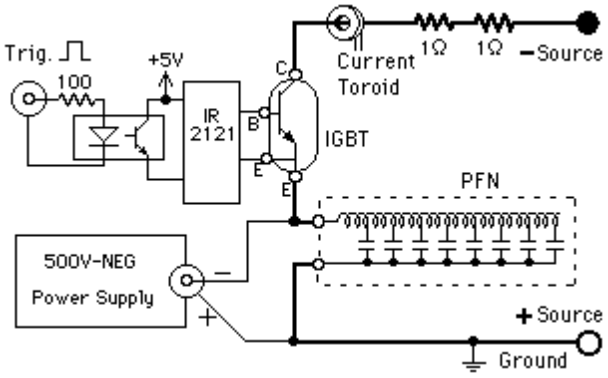

FIG 4. Basic arc modulator circuit

100-300 V at 360 Hz with occasional 20 kV sparking conditions. The complete unit is less than 9 inches high in a standard chassis and gives off very little heat. Our modulator uses a Toshiba IGBT 300Q1US1. It is capable of pulsing 600 A and withstanding 1000 V. The gate triggering unit requires 5 V to hold the IGBT on.

VI. $^3He^{++}$ PRODUCTION

Obtaining ~20 mA of $^3He^{++}$ directly from an ion source was and still is considered difficult and costly. Instead, $^3He^{++}$ is obtained by accelerating $^3He^{+}$ from the duoplasmatron source to 1 MeV using an RFQ accelerator. Unfortunately the RFQ is limited to ~15-mA output. Of this 70% can be stripped to $^3He^{++}$ using a pulsed gas stripper.[6] In this application we consider this the source for ~21 mA (electrical) of $^3He^{++}$ ions. The emittance at 1 MeV following the first RFQ is 3.4 π cm mr for 90% of the beam. No change in the emittance is observed for the fully stripped beam passing through the gas stripper.

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